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Remarks

Claims 1 - 35 are now in the application; claims 10 - 17 having been withdrawn as being directed to a nonelected invention, claims 1 - 9 and 18 - 35 are now under consideration in the application. Reconsideration of the application, as amended, is requested.

Applicant's invention provides for improved flip chip electrical interconnection between an integrated circuit chip and a substrate. The chip is provided with a first member (such as a bump), made of a deformable material (such as gold) and the substrate is provided with a second member (such as a conductive lead or pad or via opening). The first member is characterized by having a low yield strength and a high elongation to failure. The second member may be provided with surface asperities, or by having an edge, on the part of the second member to be electrically connected with the first member. To form the electrical interconnect the first and second members are pressed against one another using a force sufficient to cause **plastic flow of part of the first member into surface asperities** on the second member, or to cause **plastic flow of part of the first member around an edge** on the second member. (See, e.g., Applicant's paragraphs [0004] and [0005].)

As Applicants specification points out, the force and temperature requirements necessary to effect the interconnection are significantly lower than needed for conventional thermo-compression bonds, which require metallurgical diffusion of mating materials. This can greatly reduce damage to the chip that might otherwise occur.

The plastic deformation, according to Applicant's invention, is distinct from metallurgical connections formed by melting the bump material (solder interconnection), as well as from methods employing a curable film or paste containing conductive particles. (See, e.g., Applicant's paragraph [0003].)

As is well-known, "plastic flow" is a characteristic of solid materials. "Plastic flow" is defined, for example, in the *Academic Press Dictionary of Science and Technology*, Christopher Morris, ed., Academic Press, 1992 at page 1668 (copy attached hereto as Appendix A), as "a phenomenon in which solids may undergo a variety of extensive, irreversible deformations after the applied stress reaches a critical value." Chapter 6 of *The Science and Engineering of Materials*, D.R. Askelund *et al.*, Brooks/Cole, 2003 at pages 231 *et seq.* (copy attached as Appendix B) has as its subject the various "Mechanical Properties and Behavior of Materials,"

including, for instance, plastic deformation (pp. 235-236). Plastic flow in a material characterizes a process that is distinct from, and has nothing to do with, melting the material.

The points raised by the Examiner will now be addressed.

Rejections under 35 U.S.C. § 102(b)

Claims 1, 3, 22 and 24 were rejected under 35 U.S.C. § 102(b) as being anticipated by Caillat U.S. 5,879,530 ("Caillat").

This rejection is traversed. Caillat describes an interposer film between die and substrate, and interconnection by solder reflow. It has nothing to do with plastic deformation of a bump on an integrated circuit chip. The Examiner refers, particularly, to Caillat Figs. 7B and 7C. Caillat describes the process illustrated in these Figs. in the paragraphs beginning at Col. 5, line 27 and at Col. 5, line 49, as follows (emphasis added):

The assembly process for a substrate and a chip, both provided with contact pads, with the aid of an anisotropic conductive film as described hereinbefore will now be discussed. This process is illustrated, for certain of its stages, in FIGS. 7a to 7c. Thus, there is a substrate 2 provided with facing or aligned pads 6, 8 in front of the pads 10, 12 of a chip 4. These pads are e.g. of aluminium. It can be advantageous to cover these pads with attachment or bonding layers 56, 58, 60, 62 for brazing or attaching the **meltable materials** 44, 54. For example, it is possible, by using an "ELECTROLESS" process, to produce a Ni--Au or NiAg or NiSn or (CrCu)--Cu bi-layer, which can serve as a diffusion barrier and as a brazable material for the meltable materials 44, 54 of the nails 51. However, if the meltable materials 44, 54 can be directly brazed onto the pads, there is no need for such an attachment layer.

...

Finally, in FIG. 7c, the assembly is subjected to an assembly **temperature equal to or higher than the melting points of the two meltable materials** if the polymer has been previously completely polymerized, or **the melting points of the two meltable materials** and the final polymerization temperature of the polymer if the latter has not been previously completely polymerized.

Thus, Caillat teaches interconnect formation by solder reflow, and not by plastic deformation, as in Applicant's invention as claimed. Caillat is directed to a solder reflow process (employing an

interposer film), and cannot teach or suggest Applicant's interconnection by plastic deformation of a deformable material.

Accordingly, Caillat does not teach or suggest Applicant's invention as claimed in Applicant's claims, either as originally filed or as amended, and the rejection of claims 1, 3, 22 and 24 for anticipation by Caillat should be withdrawn.

Claims 1, 2, 4, 7 - 9, 18 - 23, 25 and 28 - 35 were rejected under 35 U.S.C. § 102(e) as being anticipated by Capote U.S. 6,335,571 ("Capote").

This rejection is traversed. Capote describes forming interconnection by reflowing a solder bump (melting the solder). It has nothing to do with plastic deformation of the bump. The Examiner refers particularly, for example, to Capote Col. 12, line 36. The paragraph beginning at that point in Capote states (emphasis added):

As in FIG. 11, the **solder bumps** 108 on the chip were aligned to the metallization pads 106 on the substrate and the two parts were squeezed together thereby moving the solder 108 bumps into intimate contact with the soldering pads 106. During this operation, care was taken so as not to entrap any air in the interface between the substrate and chip. The **solder was then reflowed in a convection/infra-red belt oven** having a thermal reflow cycle as shown in FIG. 30. The **process caused the solder bumps to melt** and wet the metallized soldering pads and also to harden the two encapsulant portions, as shown in FIG. 12. Subsequently, the assemblies were post-cured for 2 hours at 165 °C.

Further, at Col. 16, lines 1 - 5, Capote states:

The openings were then filled with solder paste ... by stencil printing. The wafers were then passed through a solder reflow cycle, similar to that shown in FIG. 30, in a nitrogen atmosphere to create the solder bumps.

Thus, Capote teaches nothing with regard to forming an interconnect by plastic deformation of a first part into asperities, or around an edge, of a second part. The feature 108 in Capote is in every instance a solder bump, connected to the feature 106 by solder reflow (step shown for instance in Capote Figs. 11 - 12; 14 - 15). The liquid encapsulant 109 in Capote contains solder flux. Capote is directed to solder reflow process, and cannot teach or suggest Applicant's invention by plastic deformation of a deformable material.

Accordingly, Capote does not teach or suggest Applicant's invention as claimed in Applicant's claims, either as originally filed or as amended, and the rejection of claims 1, 2, 4, 7 - 9, 18 - 23, 25 and 28 - 35 for anticipation by Capote should be withdrawn.

Rejections under 35 U.S.C. § 103(a)

Claims 5 and 26 were rejected under 35 U.S.C. § 103(a) for obviousness over Capote in view of Yuzawa *et al.* U.S. 6,335,568 ("Yuzawa"). The Examiner applies Capote as in the rejections (see above) for anticipation, acknowledging that Capote "fails to teach that the second member is a lead." Claims 6 and 27 were rejected under 35 U.S.C. § 103(a) for obviousness over Capote in view of Murakami U.S. 5,874,780 ("Murakami"). The Examiner applies Capote as in the rejections (see above) for anticipation, acknowledging that Capote "[does] not teach that the second member is a via opening."

These rejections are traversed. As noted above, Capote describes solder reflow, and therefore Capote cannot substantially teach or suggest Applicant's invention as claimed. Neither Yuzawa nor Murakami can supply what Capote lacks in this regard, and no combination of Capote with Murakami or with Yuzawa makes Applicant's claimed invention either as originally filed or as amended. Accordingly, these rejections should be withdrawn.

Additionally, neither Murakami nor Yuzawa teaches or suggests surface asperities on a surface of the second member. Nor does either Murakami or Yuzawa teach or suggest a second member having a surface adjacent an edge, and pressing the first and second members against one another with sufficient force to cause plastic deformation of the first member around the edge. The Examiner has mischaracterized ("Response to Arguments") Applicant's earlier remarks with respect to "asperities", as a re-reading of Applicant's remarks will show; those Remarks were directed to explanation of the ordinary meaning of "asperities", and not to asperities necessarily having jagged lines.

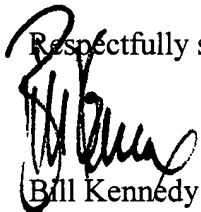
In view of the foregoing, it is believed that all the claims now under consideration, namely claims 1 - 9, 18 - 35, are in condition for allowance, and action to that effect is requested.

This Response is being filed within the second month following the shortened statutory period set by the Examiner for response and, accordingly, it is accompanied by a petition for two months' extension of time and a fee or fee authorization therefor. In the event the Petition may become separated from this paper, or if the Examiner determines that additional extension of time be required in connection with this paper, Petition is hereby made therefor, and the Commissioner is authorized to charge any fee therefor, or any other additional fee the Examiner may determine may be required in connection with this paper, to Deposit Account No. 50-0869 (Order No. CPAC 1003-1).

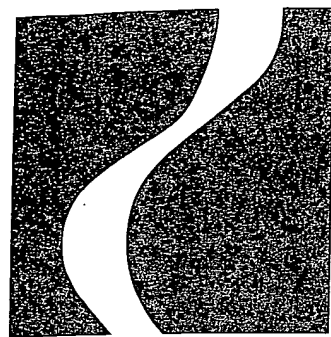
This Response is also accompanied by a Notice of Appeal and a fee or fee authorization therefor.

If the Examiner determines that a conference would facilitate prosecution of this application, the Examiner is invited to telephone Applicants' representative, undersigned, at the telephone number set out below.

Respectfully submitted,

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Edited by
Christopher Morris



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plastic flow *Physics*. a phenomenon in which solids may undergo a variety of extensive, irreversible deformations after the applied stress reaches a critical value.

Plasticine *Materials*. the trade name for a synthetic substitute for modeling clay.

plastic instability *Materials Science*. severe localization of the plastic deformation in materials under tensile stresses (necking); because of the decreased cross-sectional area, the true stress increases tend to fracture them.

plasticity *Mechanics*. the fact of being plastic; the property of a body by which it undergoes plastic deformation when the applied stress exceeds a certain value, known as the yield value.

plasticity index *Geology*. the range of water content at which a soil behaves plastically, equal to the percentage difference between the liquid limit and the plastic limit.

plasticization *Materials Science*. a process used to lower glass transition temperature; it improves the flexibility of certain polymers, allowing them to remain flexible well below the glass transition temperature of unplasticized materials.

plasticize *Engineering*. to make a material malleable by mixing it with a plasticizer, or by applying heat.

plasticizer *Engineering*. a material, usually organic, that is capable of imparting flexibility to nonplastic material or improving the flexibility of ceramic mixtures. *Materials Science*. see WATER REDUCER.

plasticlast *Geology*. an intraclast made up of calcareous mud that was fragmented while still soft.

plastic limit *Geology*. the minimum amount of water mixed with a given sediment or soil that enables the soil to be rolled into a thin thread, without breaking the thread.

plasticorder *Engineering*. an instrument that measures the temperature, viscosity, and shear-rate relationships of a plastic substance to determine its eventual behavior.

plasticoviscosity *Mechanics*. the property of a material whose rate of plastic deformation when subjected to stresses exceeding the yield stress is a linear function of the applied stresses.

plastic paint *Materials*. a thick-texture paint that can be worked to a patterned finish.

plastic plate *Electronics*. a collection of dielectric materials used as a base for a semiconductor device. *Graphic Arts*. 1. a direct offset-printing plate made on paper or other material coated with a thermoplastic vinyl resin; used for short, medium-quality press runs. 2. a molded printing plate made by pouring thermosetting plastic powder into a plastic mold; used for long press runs of type and simple line art.

plastics *Materials Science*. materials of high molecular weight that consist primarily of synthetic polymers or condensates, which can be shaped by flow into objects of diverse shapes and sizes.

plastic strain *Materials Science*. a permanent displacement of material, as in slip or twinning; the displacement remains after the stress has been removed.

plastic surgeon *Surgery*. a specialist in plastic surgery.

plastic surgery *Surgery*. a surgical procedure to repair, remodel, or restore defective or injured tissue or body parts or to improve their shape or appearance. Also, **plastic operation**.

Plastic Wood *Materials*. the trade name for a compound that is used to patch and fill woodwork.

plastic wrap *Materials*. a thin, transparent sheet of plastic that can cling to other substances; used to wrap and store food and for microwave cooking.

plastic zone *Geology*. in an explosion crater, a region bordering the rupture zone at an increased distance from the shock site, having less fracturing than and only small permanent deformations in comparison to the rupture zone. *Materials Science*. a heavily plastically deformed region in a material, generally adjacent to the tip of a crack that can cause crack-tip blunting.

plastid *Cell Biology*. any of a number of membrane-bound organelles found in plant cells and performing a specific function for the cell, such as a photosynthetic chloroplast.

plastify see PLASTICATE.

plastisol *Materials*. a dispersion of resin in a plasticizer that gels when heated.

plastocyanin *Biochemistry*. a blue, copper protein that transports electrons in chloroplast membranes from photosystem I to photosystem II during photosynthesis.

plastogene *Cell Biology*. a gene located in a plastid of a plant cell rather than in the nucleus.

plastoglobuli *Biochemistry*. a group of globules, found in plastids, that contain principally lipid.

plastome *Molecular Biology*. the genetic complement of a plastid.

plastometer *Engineering*. 1. an instrument used to measure the viscosity or flexibility of a material. 2. an instrument that measures the flow characteristics of a thermoplastic resin as it moves through an orifice at a certain pressure and temperature. 3. a machine for determining the stress and strain properties of metals at high temperatures and at various rates of strain.

plastron *Vertebrate Zoology*. the ventral portion of the shell of a turtle or tortoise, composed of four bony plates and covered with epidermal scales. *Invertebrate Zoology*. 1. in some adult aquatic insects, a thin layer of gases held in place by extremely fine, charged hairs on the body surface, to allow for respiration when the insect is submerged. 2. in heart urchins, a modified plate on the underside. 3. in spiders, a ventral plate on the cephalothorax.

plat *Cartography*. a plan drawn to scale that shows the boundaries and subdivisions of a piece of land, intended for use during development or sale of that land, and not necessarily showing other planimetric, relief, or cultural detail.

Plata see RIO DE PLATA.

Platacidae *Vertebrate Zoology*. an equivalent name for Ogcocephalidae, a family of marine fishes commonly known as batfishes.

Platanaceae *Botany*. a family of monoecious dicotyledonous trees in the order Hamamelidales, having simple deciduous leaves, large and conspicuous stipules, and small, densely clustered fruit.

Platanistidae *Vertebrate Zoology*. the freshwater or river dolphins, a family of toothed whales of the order Odontoceta, characterized by a long, slender rostrum, and a prominent bulge on the forehead; found in southern Asia and South America.

Plataspidae *Invertebrate Zoology*. shiny, oval, true bugs, a family of hemipteran insects in the superfamily Pentatomoidea.

platband *Architecture*. 1. a flat structural member, as a lintel or flat band. 2. a shallow molding having a flat face.

plate any of various thin, flat objects or devices, such as the large, circular dish on which food is served; specific uses include: *Metallurgy*. a thin, flat piece of metal, especially one used to provide support or protection of a surface, fitting, or joint. *Building Engineering*. a base member, as of a partition or other frame. *Anatomy*. a flat structure or layer, such as a thin layer of bone. *Medicine*. a hard fitting to which artificial teeth are attached. *Graphic Arts*. 1. also, **printing plate**. a surface that can be etched or engraved (by hand, mechanically, or photographically) and from which impressions onto another surface can be made for the purpose of printing. 2. also, **photographic plate**. a glass plate coated with photosensitive emulsion; an earlier form of photographic film, still used with nuclear emulsions to track charged particles. 3. an illustration in a book, especially a color illustration. *Electricity*. 1. the electrode in a cell, battery, or tube toward which current flows or to which electrons are attracted; an anode. 2. of or relating to an anode. Thus, **plate current**, **plate efficiency**, **plate modulation**, **plate neutralization**, **plate power**, **plate saturation**, and so on. *Horology*. the solid base onto which are mounted the wheels, pinions, springs, and screws that compose the movement of a timepiece. *Geology*. 1. one of several large, mobile blocks of continental or oceanic crust, together with some portion of the asthenosphere, that move as a single, nearly rigid unit. 2. a hard, smooth, thin, flat fragment of rock or stone, such as a flagstone.

plate amalgamation *Metallurgy*. a metallic plate used for amalgamating gold with mercury.

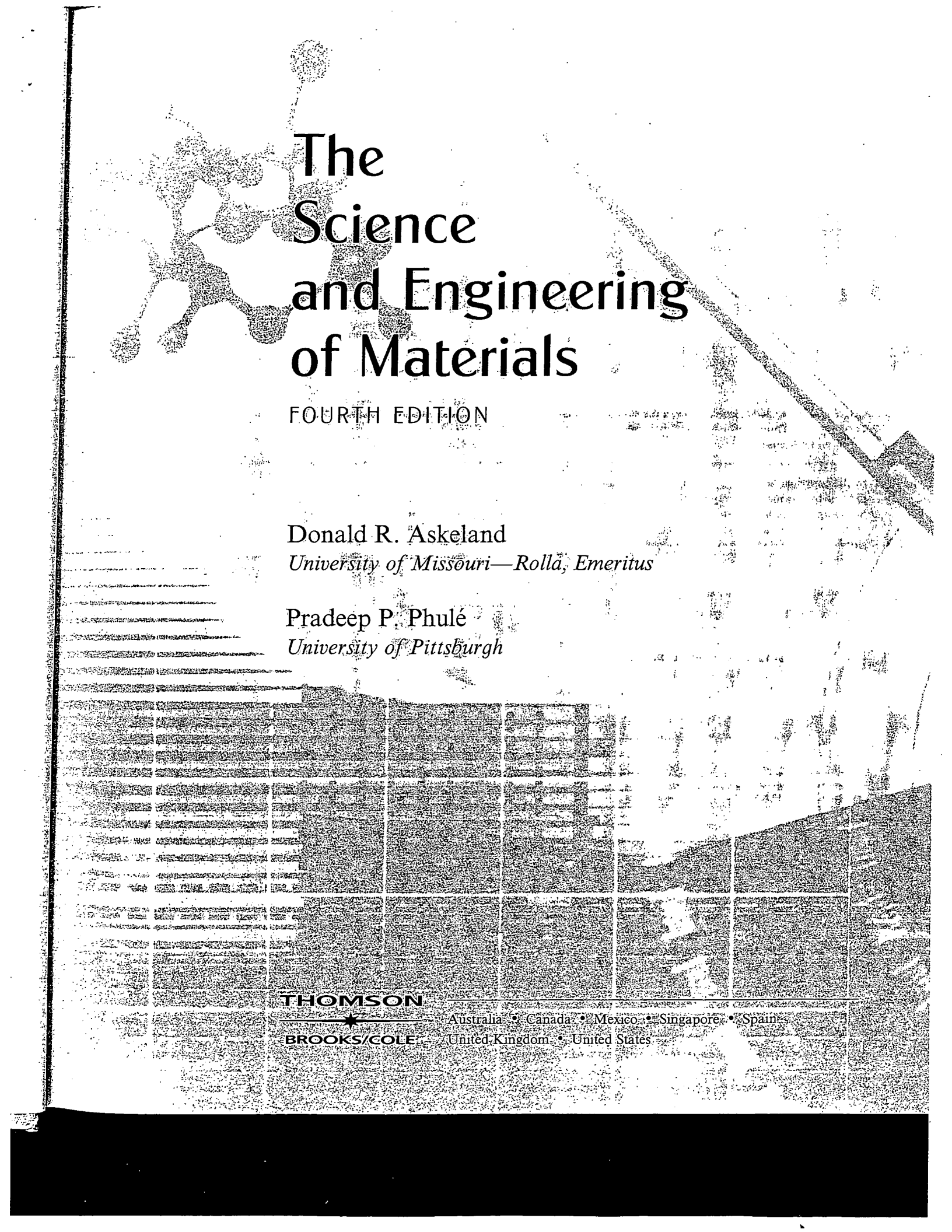
plateau *plural*, **plateaus** or **plateaux**. *Geology*. an extensive, nearly level land area, with at least one steep side, that is higher than the surrounding area and usually at least 2000 feet above sea level. *Electronics*. the point in a response curve where an increase in the independent variable no longer affects the dependent variables. (From the French word for "plate.")

plateau basalt *Geology*. a large, extensive basaltic lava flow or series of flows from fissure eruptions that accumulate to form a plateau. Also, **FLOOD BASALT**.

plateau characteristic *Electronics*. a relationship between two variables in which the dependent variable reaches a value that does not change with further increase of the independent variable.

plateau glacier *Hydrology*. a glacier formed on a mountain plateau, usually overflowing the edges in hanging glaciers.

plateau gravel *Geology*. a sheet or patch of surficial gravel on a plateau or other region above the height at which stream-terrace gravel is usually found.



The Science and Engineering of Materials

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Mechanical Properties and Behavior

Have You Ever Wondered?

- Why Silly Putty® can be stretched a considerable amount when pulled slowly, but snaps when pulled fast?
- Why is it that glass fibers of different lengths have different strengths?
- Why we can load the weight of a fire truck on four ceramic coffee cups, however, ceramic cups tend to break easily when we drop them on the floor?
- What materials-related factors played an important role in the sinking of the Titanic?
- What factors played a major role in the 1986 Challenger space shuttle accident?
- Why does latex paint feel thinner when you stir it?
- Why do some metals and plastics become brittle at low temperatures?
- Why do aircrafts have a finite service life?

The mechanical properties of materials depend on their composition and microstructure. In Chapters 2, 3, and 4, we learned that a material's composition, nature of bonding, crystal structure, and defects such as dislocations, grain size, etc., have a profound influence on the strength and ductility of metallic materials. In this chapter, we

will begin to evaluate other factors that affect the mechanical properties of materials, such as how lower temperatures can cause many metals and plastics to become brittle. Lower temperatures contributed to the brittleness of the plastic used for the O-rings, causing the 1986 *Challenger* accident.[1] Similarly, the special chemistry of the

steel used on the *Titanic* and the stresses associated in the fabrication and embrittlement of this steel when subjected to lower temperatures have been identified as factors contributing to the failure of the ship's hull.[2,3] Some researchers have shown that weaker rivets and design flaws also contributed to the failure.

The main goal of this chapter is to introduce the basic concepts associated with me-

chanical properties. We will learn basic terms such as hardness, stress, strain, elastic and plastic deformation, viscoelasticity, strain rate, fracture toughness, fatigue, creep, etc. We will also review some of the basic testing procedures that engineers use to evaluate many of these properties. These concepts will be discussed using illustrations from real-world applications.

6-1

Technological Significance

With many of today's emerging technologies, the primary emphasis is on the mechanical properties of the materials used. For example, in aircraft manufacturing, aluminum alloys or carbon-reinforced composites used for aircraft components must be lightweight, strong, and able to withstand cyclic mechanical loading for a long and predictable period of time (Figure 6-1). Steels used in the construction of structures such as buildings and bridges must have adequate strength so that these structures can be built without compromising safety. The plastics used for manufacturing pipes, valves, floor-



Figure 6-1 Aircraft, such as the one shown here, makes use of aluminum alloys and carbon-fiber-reinforced composites. (Courtesy of Getty Images.)

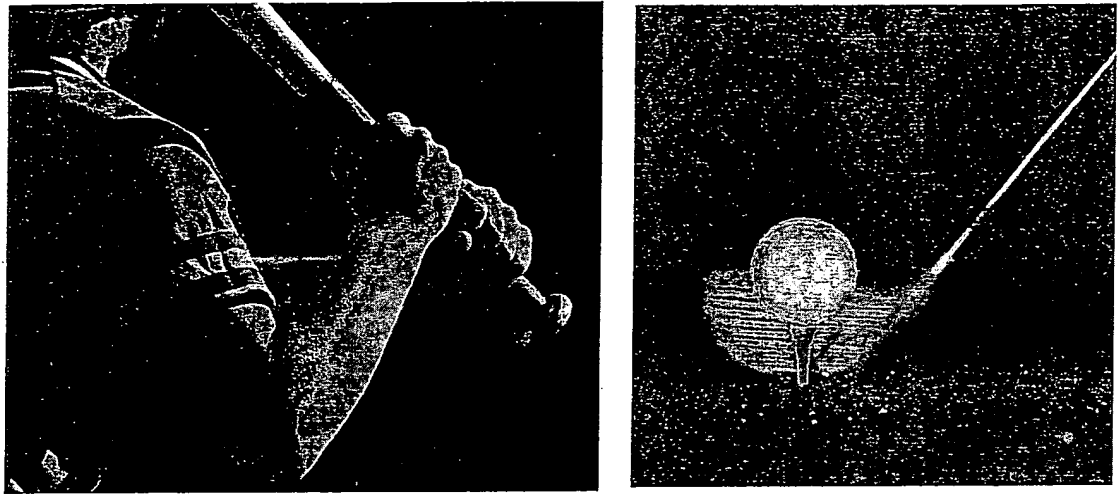


Figure 6-2 The materials used in sports equipment must be lightweight, stiff, tough, and impact resistant. (Courtesy of Getty Images.)

ing, and the like also must have adequate mechanical strength. Materials such as pyrolytic graphite or cobalt chromium tungsten alloys, used for prosthetic heart valves, must not fail.[4] Similarly, the performance of baseballs, cricket bats, tennis rackets, golf clubs, skis, and other sport equipment depends not only on the strength and weight of the materials used, but also on their ability to perform under an “impact” loading (Figure 6-2). The importance of mechanical properties is easy to appreciate in many of these “load-bearing” applications.

In Chapters 1 and 2, we learned that advanced engineered materials are used for technologies that capitalize on the electronic, magnetic, optical, biological, and other properties. In most of these applications, the mechanical properties of the material also play an important role. For example, an optical fiber must have a certain level of strength to withstand the stresses encountered in its application. A biocompatible titanium alloy used for a bone implant must have enough strength and toughness to survive in the human body for many years without failure. A scratch-resistant coating on optical lenses must resist mechanical abrasion. An aluminum alloy or a glass-ceramic substrate used as a base for building magnetic hard drives must have sufficient mechanical strength so that it will not break or crack during operation that requires rotation at high speeds. Similarly, electronic packages used to house semiconductor chips and the thin-film structures created on the semiconductor chip must be able to withstand stresses encountered in various applications, as well as those encountered during the heating and cooling of electronic devices. The mechanical robustness of small devices prepared using micro-electro mechanical systems (*MEMS*) and nano-technology is also important. Float glass used in automotive and building applications must have sufficient strength and shatter resistance. Many components designed from plastics, metals, and ceramics must not only have adequate toughness and strength at room temperature but also at relatively high and low temperatures. The point we want to make is very simple. The mechanical properties of a material and that of a component are critical in many applications in which the functional emphasis may be on the electronic, optical, magnetic, biological or some other properties.

For load-bearing applications, engineered materials are selected by matching their mechanical properties to the design specifications and service conditions required of the

component. The first step in the selection process requires an analysis of the material's application to determine its most important characteristics. Should it be strong, stiff, or ductile? Will it be subjected to an application involving high stress or sudden intense force, high stress at elevated temperature, cyclic stresses, corrosive or abrasive conditions? Once we know the required properties, we can make a preliminary selection of the appropriate material using various databases. We must, however, know how the properties listed in the handbook are obtained, know what the properties mean, and realize that the properties listed are obtained from idealized tests that may not apply exactly to real-life engineering applications. Materials with the same nominal chemical composition and other properties can show significantly different mechanical properties as dictated by microstructure. Furthermore, changes in temperature; the cyclical nature of stresses applied; the chemical changes due to oxidation, corrosion, or erosion; microstructural changes due to temperature; the effect of possible defects introduced during machining operations (e.g., grinding, welding, cutting, etc.); or other factors can also have a major effect on the mechanical behavior of materials. A competent professional engineer will be aware of these possibilities and be able to take these into account, along with safety, cost, environmental impact, and other requirements when designing and fabricating different components.

The mechanical properties of materials must also be understood so that we can process materials into useful shapes using materials processing techniques. Materials processing such as the use of steels and plastics to fabricate car bodies, requires a detailed understanding of the mechanical properties of materials at different temperatures and conditions of loading, for example, the mechanical behavior of steels and plastics used to fabricate such items as aerodynamic car bodies. One of the reasons we draw, roll, forge, extrude, and stamp steels and many other alloys by first heating them to high temperatures is that they become ductile at high temperatures. Similarly, we make use of favorable changes in properties of plastics and glasses during their processing into different shapes (e.g., optical fibers).

In the sections that follow, we discuss mechanical properties of materials. We will define and discuss different terms that are used to describe the mechanical properties of engineered materials. Different tests used to determine mechanical properties of materials are discussed.

6-2

Terminology for Mechanical Properties

There are different types of forces or "stresses" that are encountered in dealing with mechanical properties of materials. In general, we define **stress** as force acting on the unit area over which the force is applied. Tensile, compressive, shear, and bending stresses are illustrated in Figure 6-3(a). **Strain** is defined as the change in dimension per unit length. Stress is typically expressed in psi (pounds per square inch) or Pa (Pascals). Strain has no dimensions and is often expressed as in./in. or cm/cm.

When discussing stress and strain, it may be useful to think about stress as the *cause* and strain as the *effect*. Typically, tensile and shear stresses are designated by the symbols σ and τ , respectively. Tensile and shear strains are represented by the symbols ϵ and γ , respectively. Many load-bearing applications involve tensile or compressive stresses. Shear stresses are often encountered in the processing of materials using such techniques as polymer extrusion. Shear stresses are also found in structural applications. Note that even a simple tensile stress applied along one direction will cause a shear stress to components in other directions (similar to the situation discussed in Schmid's law, Chapter 4).

F-

Stress σ

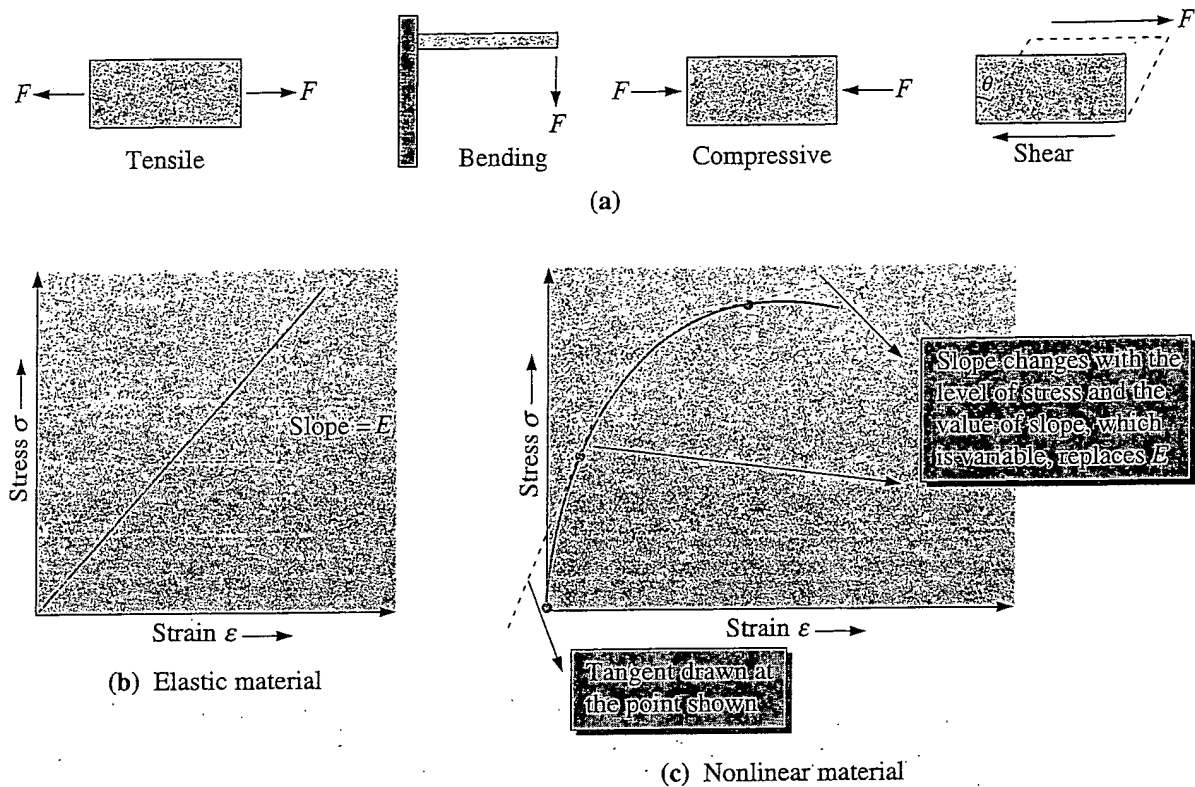


Figure 6-3 (a) Tensile, compressive, shear and bending stresses. (b) Illustration showing how Young's modulus is defined for an elastic material. (c) For nonlinear materials, we use the slope of a tangent as a variable quantity that replaces the Young's modulus constant.

Elastic strain is defined as fully recoverable strain resulting from an applied stress. The strain is "elastic" if it develops instantaneously (i.e., the strain occurs as soon as the force is applied), remains as long as the stress is applied, and is removed as soon as the force is withdrawn. A material subjected to an elastic strain does not show any permanent deformation (i.e., it returns to its original shape after the force or stress is removed). Consider stretching a stiff metal spring by a small amount and letting go. If the spring goes back quickly to its original dimensions, the strain developed in the spring was elastic.

In many materials, elastic stress and elastic strain are linearly related. The slope of a tensile stress-strain curve in the linear regime defines the **Young's modulus** or **modulus of elasticity** (E) of a material [Figure 6-3(b)]. The units of E are measured in pounds per square inch (psi) or Pascals (Pa) (same as those of stress). Large elastic deformations are observed in **elastomers** (e.g., natural rubber, silicones), where the relationship between elastic strain and stress is non-linear. In elastomers, the large elastic strain is related to the coiling and uncoiling of spring-like molecules (Chapter 15). In dealing with such materials, we use the slope of the tangent at any given value of stress or strain and consider that as a variable quantity that replaces the Young's modulus [Figure 6-3(c)]. The inverse of Young's modulus is known as the **compliance** of the material. Similarly, we define **shear modulus** (G) as the slope of the linear part of the shear stress-shear strain curve.

Permanent or **plastic deformation** in a material is known as the **plastic strain**. In this case, when the stress is removed, the material does *not* go back to its original shape.

A dent in a car is plastic deformation! Note that the word “plastic” here does not refer to strain in a plastic (polymeric) material, but rather to a type of strain in any material.

The rate at which strain develops in a material is defined as **strain rate** ($\dot{\epsilon}$ or $\dot{\gamma}$ for tensile and shear strain rates, respectively). Units of strain rate are s^{-1} . You will learn later in this chapter that the rate at which a material is deformed is important from a mechanical properties perspective. Many materials considered to be ductile, behave as brittle solids when the strain rates are high. Silly Putty® (a silicone polymer) is an example of such a material. When stretched slowly (smaller rate of strain), we can stretch this material by a large amount. However, when stretched rapidly (high strain rates), we do not allow the untangling and extension of the large polymer molecules and, hence, the material snaps. When the strain rates are low, Silly Putty® can show significant ductility. When materials are subjected to high strain rates we refer to this type of loading as **impact loading**.

A **viscous material** is one in which the strain develops over a period of time and the material does not go to its original shape after the stress is removed. The development of strain takes time and is not in phase with the applied stress. Also, the material will remain deformed when the applied stress is removed (i.e., the strain will be plastic). A **viscoelastic** (or **anelastic**) material can be thought of as a material whose response is between that of a viscous material and an elastic material. The term “anelastic” is typically used for metals, while the term “viscoelastic” is usually associated with polymeric materials. Many plastics (solids and molten) are viscoelastic. A common example of a viscoelastic material is Silly Putty®.

In a viscoelastic material, the development of a permanent strain is similar to that in a viscous material. However, unlike a viscous material, when the applied stress is removed, part of the strain will recover over a period of time. Recovery of strain refers to a change in shape of a material after the stress causing deformation is removed. A qualitative description of development of strain as a function of time in relation to an applied force in elastic, viscous, and viscoelastic materials is shown in Figure 6-4. In viscoelastic materials held under constant strain, if we wait, the level of stress decreases over a period of time. This is known as **stress relaxation**. Recovery of strain and stress relaxation are different terms and should not be confused. A common example of stress relaxation is the nylon strings strung in a tennis racket. We know that the level of stress, or the “tension”, as the tennis players call it, decreases with time.

While dealing with molten materials, liquids, and dispersions, such as paints or gels, a description of the resistance to flow under an applied stress is required. If the relationship between the applied stress and **shear strain rate** ($\dot{\gamma}$) is linear, we refer to that material as **Newtonian**. The slope of the shear stress versus the steady-state shear strain rate curve is defined as the **viscosity** (η) of the material. Water is an example of a Newtonian material. The following relationship defines viscosity:

$$\tau = \eta \dot{\gamma} \quad (6-1a)$$

The units of η are Pa-s (in the SI system) or Poise (P) or $\frac{g}{cm \cdot s}$ in the cgs system. Sometimes the term centipoise (cP) is used, $1 \text{ cP} = 10^{-2} \text{ P}$.

Conversion between these units is given by $1 \text{ Pa-s} = 10 \text{ P} = 1000 \text{ cP}$.

The **kinematic viscosity** (ν) is defined as:

$$\nu = \eta / \rho \quad (6-1b)$$

where viscosity (η) is in Poise and density (ρ) is in g/cm^3 . The kinematic viscosity unit is in Stokes (St). In this, St is cm^2/s . Sometimes the unit of centiStokes (cSt) is used, $1 \text{ cSt} = 10^{-2} \text{ St}$.

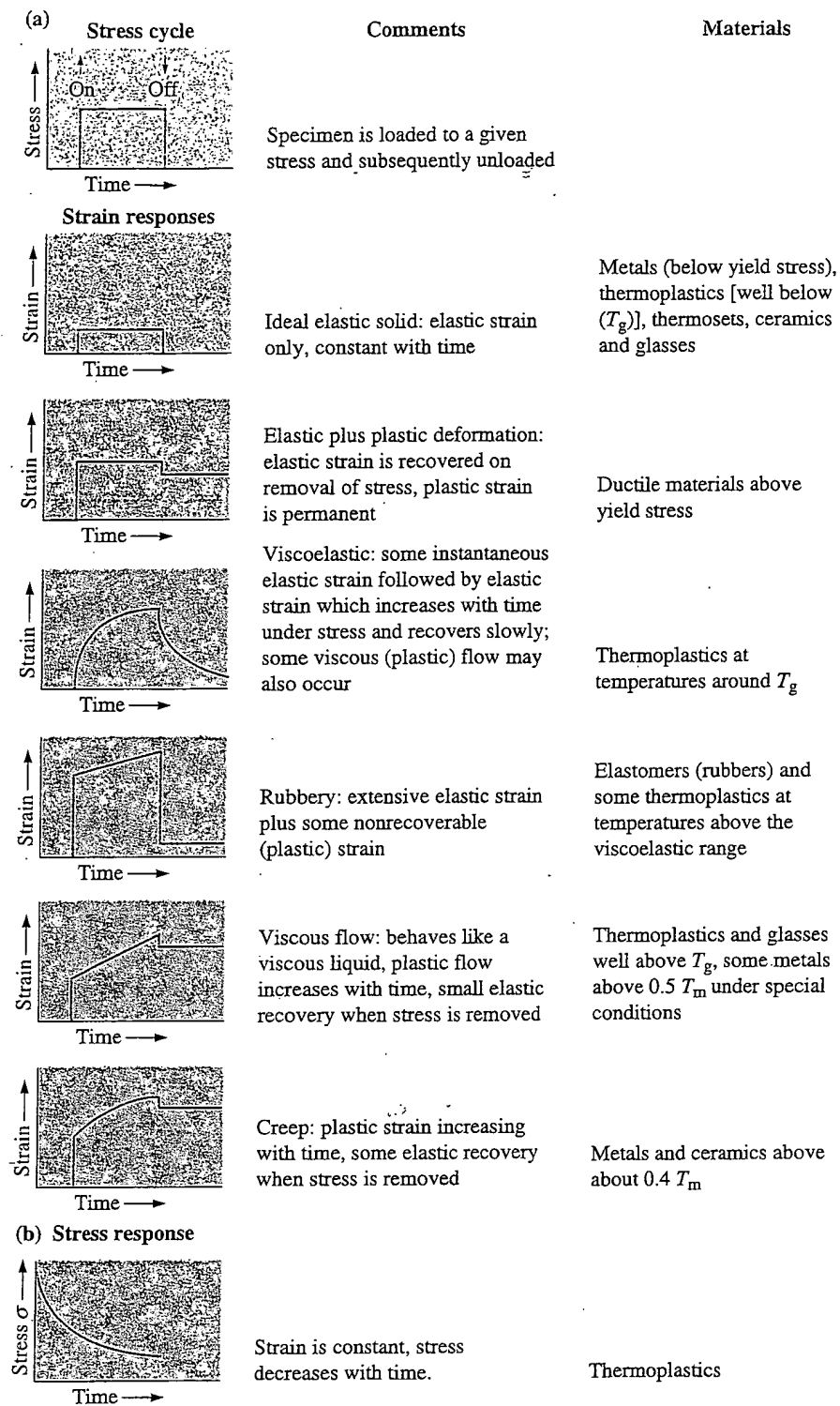


Figure 6-4 (a) Various types of strain response to an imposed stress. (Source: Reprinted from *Materials Principles and Practice*, by C. Newey and G. Weaver (Eds.), 1991 p. 300, Fig. 6-9. Copyright © 1991 Butterworth-Heinemann. Reprinted with permission from Elsevier Science.) (b) Stress relaxation in a viscoelastic material. Note the y-axis is stress. Strain is constant.

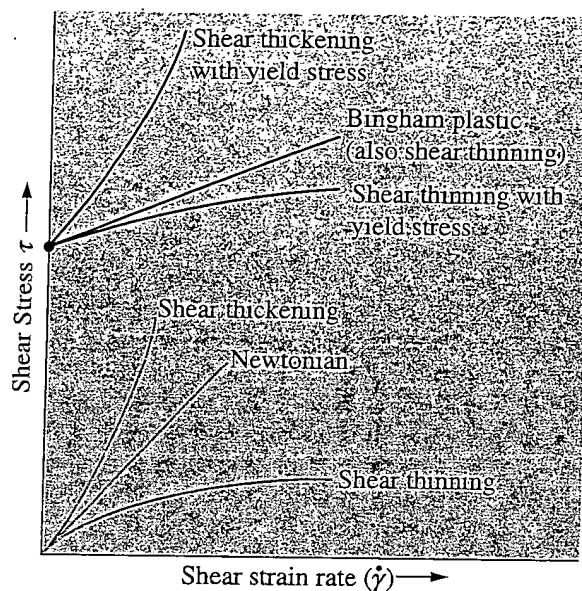


Figure 6-5
Shear stress-shear strain rate
relationships for Newtonian and non-
Newtonian materials.

For many materials the relationship between shear stress and shear strain rate is nonlinear. These materials are **non-Newtonian**. The stress versus steady state shear strain rate relationship in these materials can be described as:

$$\tau = \eta \dot{\gamma}^m \quad (6-2)$$

where the exponent m is not equal to 1.

Non-Newtonian materials are classified as **shear thinning** (or pseudo-plastic) or **shear thickening** (or dilatant). The relationships between the shear stress and shear strain rate for different types of materials are shown in Figure 6-5. As shown in Figure 6-6(a), the **apparent viscosity** (η_{app}) of the material decreases with increasing steady-state shear strain rate. If we take the slope of the line obtained by joining the origin to any point on the curve what we determine is the apparent viscosity. The apparent viscosity of a Newtonian material will remain constant with changing shear strain rate. In shear thinning materials, the apparent viscosity decreases with increasing shear strain rate. In shear thickening materials the apparent viscosity increases with increasing shear strain rate. If you have a can of paint sitting in storage, for example, the shear strain rate that the paint is subjected to is very small and the paint behaves as if it is very viscous. When you take a brush and paint, the paint is subjected to high shear strain rate. The paint now behaves as if it is quite thin or less viscous (i.e., it exhibits a small apparent viscosity). This is the shear thinning behavior.

Some materials have "ideal plastic" behavior. For an ideal plastic material the shear stress does not change with shear strain rate. Many useful materials can be modeled as **Bingham plastics** and are defined by the following equations:

$$\tau = G\gamma \quad (\text{when } \tau \text{ is less than } \tau_y) \quad (6-3a)$$

$$\tau = \tau_y + \eta \dot{\gamma} \quad (\text{when } \tau \geq \tau_y) \quad (6-3b)$$

This is illustrated in Figure 6-6(b) and 6-6(c).

In these equations, τ_y is the apparent **yield strength** obtained by interpolating the shear stress-shear strain rate data to zero shear strain rate. We define yield strength as the stress level that has to be exceeded so that the material begins to deform plastically. The existence of a true yield strength (sometimes also known as yield stress) has not

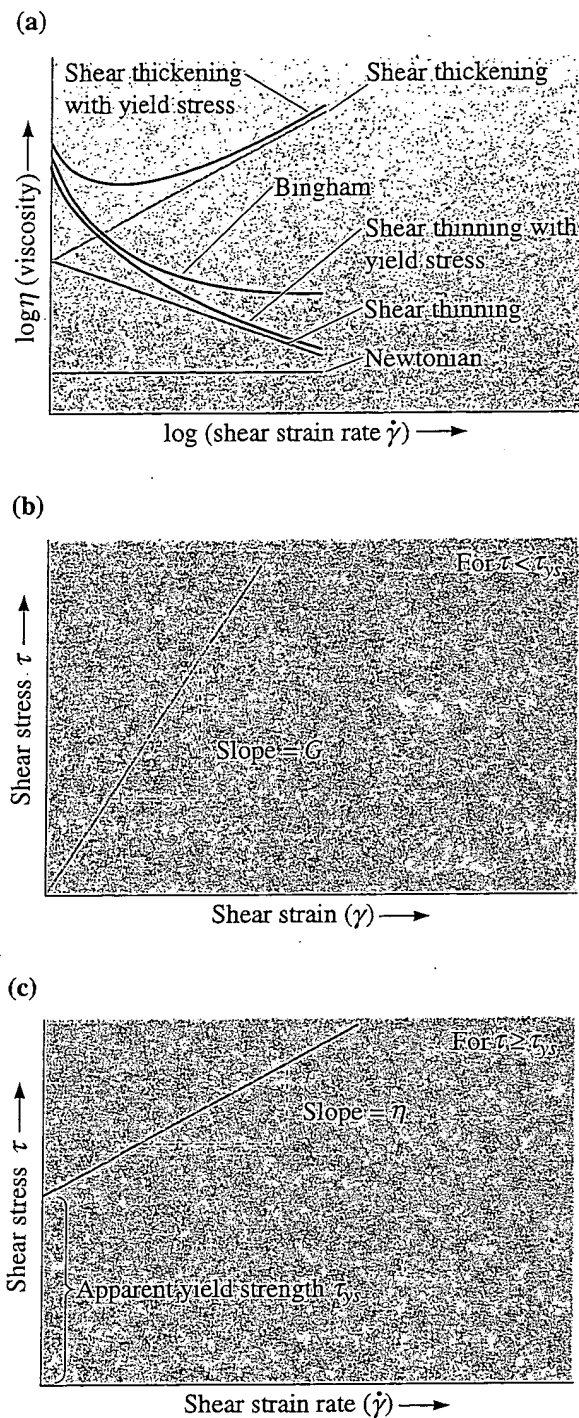


Figure 6-6

(a) Apparent viscosity as a function of shear log (shear rate $\dot{\gamma}$) strain rate. (b) and (c) illustration of a Bingham plastic (Equations 6-3a & b). Note the x-axis on (b) is shear strain.

been proven unambiguously for many plastics and dispersions such as paints. To prove the existence of yield stress, separate measurements of stress versus strain are needed. For these materials, a critical yielding strain may be a better way to describe the mechanical behavior.[5] Many ceramic slurries (dispersions such as those used in ceramic processing), polymer melts (used in polymer processing), paints and gels, and food

products (yogurt, mayonnaise, ketchups, etc.) exhibit Bingham plastic-like behavior. Note that Bingham plastics exhibit shear thinning behavior (i.e., the apparent viscosity decreases with increasing shear rate).

Shear thinning materials also exhibit a **thixotropic behavior** (e.g., paints, ceramic slurries, polymer melts, gels, etc.). Thixotropic materials usually contain some type of network of particles or molecules. When a sufficiently large shearing strain (i.e., greater than the critical yielding strain) is applied, the thixotropic network or structure breaks and the materials begin to flow. As the shearing stops, the network begins to form again and the resistance to the flow increases. The particle or molecular arrangements in the newly formed network are different from those in the original network. Thus, the behavior of thixotropic materials is said to be time and deformation history dependent. Some materials show an increase in the apparent viscosity as a function of time and at a constant shearing rate. These materials are known as **rheoplectic**.

The rheological properties of materials are determined using instruments known as a viscometer or a **rheometer**. In these instruments a constant stress or constant strain rate is applied to the material being evaluated. Different geometric arrangements (e.g., cone and plate, parallel plate, Couette, etc.) are used.

In the sections that follow, we will discuss different mechanical properties of solid materials and some of their testing methods to evaluate these properties.

6-3

The Tensile Test: Use of the Stress-Strain Diagram

The tensile test is popular since the properties obtained could be applied to design different components. The tensile test measures the resistance of a material to a static or slowly applied force. The strain rates in a tensile test are very small ($\dot{\epsilon} = 10^{-4}$ to $10^{-2} s^{-1}$). A test setup is shown in Figure 6-7; a typical specimen has a diameter of 0.505 in. and a gage length of 2 in. The specimen is placed in the testing machine and a force F , called the **load**, is applied. A universal testing machine on which tensile and compression can be performed is shown in Figure 6-8. A **strain gage** or **extensometer** is used to measure the amount that the specimen stretches between the gage marks when the force is applied. Thus, what is measured is the change in length of the specimen (Δl)

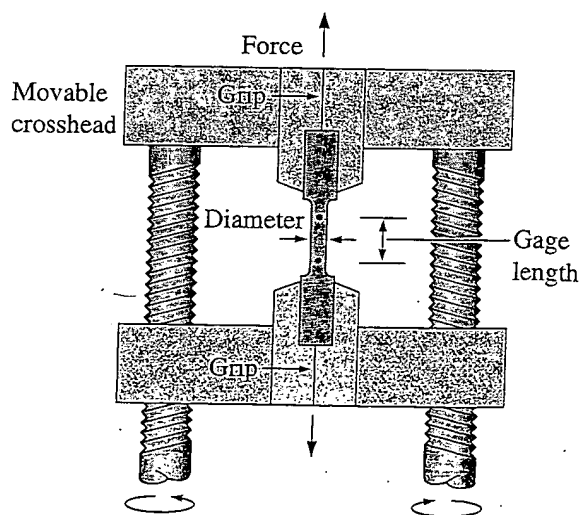


Figure 6-7

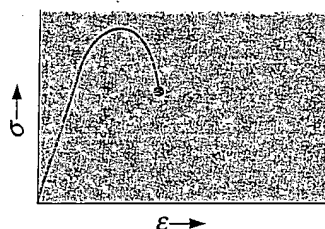
A unidirectional force is applied to a specimen in the tensile test by means of the moveable crosshead. The cross-head movement can be performed using screws or a hydraulic mechanism.



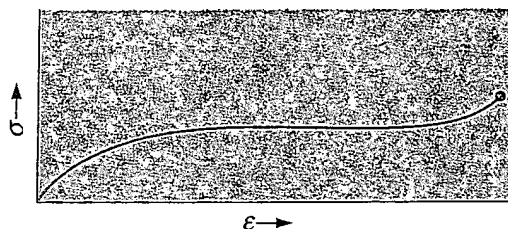
Figure 6-8 Students conducting a tensile test on an automated tensile testing machine. (Courtesy of Pradeep Phulé.)

over a particular original length (l_0). Information concerning the strength, Young's modulus, and ductility of a material can be obtained from such a tensile test. Typically, a tensile test is conducted on metals, alloys, and plastics. Tensile tests can be used for ceramics, however, these are not very popular because the sample may fracture while it is being aligned. The following discussion mainly applies to the tensile testing of metals and alloys. We will briefly discuss the stress-strain behavior of polymers as well.

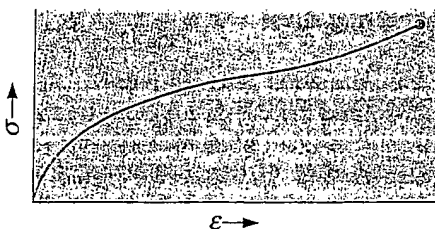
(a) Metal



(b) Thermoplastic material above T_g



(c) Elastomer



(d) Ceramics, glasses, and concrete

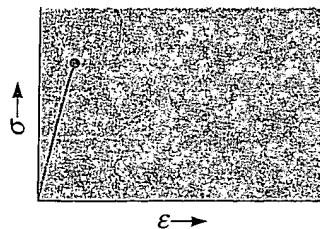


Figure 6-9 Tensile stress-strain curves for different materials. Note that these are *qualitative*.

Figure 6-9 shows *qualitatively* the stress-strain curves for a typical (a) metal, (b) a thermoplastic material, (c) an elastomer, and (d) ceramics (or glass) under relatively small strain rates. The scales in this figure are qualitative and different for each material. In practice, the actual magnitude of stresses and strains will be very different. The plastic material is assumed to be above its **glass temperature** (T_g). Metallic materials are assumed to be at room temperature. Metallic and thermoplastic materials show an initial elastic region followed by a non-linear plastic region. A separate curve for elastomers (e.g., rubber or silicones) is also included since the behavior of these materials is different from other polymeric materials. For elastomers, a large portion of the deformation is elastic and non-linear. On the other hand, ceramics and glasses show only a linear elastic region and almost no plastic deformation at room temperature.

When a tensile test is conducted, the data recorded includes load or force as a function of change in length (Δl). The change in length is typically measured using a strain gage. Table 6-1 shows the effect of the load on the changes in length of an aluminum alloy test bar. These data are then subsequently converted into stress and strain. The stress-strain curve is analyzed further to extract properties of materials (e.g., Young's modulus, yield strength, etc.).

TABLE 6-1 ■ The results of a tensile test of a 0.505-in. diameter aluminum alloy test bar, initial length (l_0) = 2 in.

Measured Change in Length (Δl)		Calculated	
Load (lb)	(in.)	Stress (psi)	Strain (in./in.)
0	0.000	0	0
1000	0.001	5,000	0.0005
3000	0.003	15,000	0.0015
5000	0.005	25,000	0.0025
7000	0.007	35,000	0.0035
7500	0.030	37,500	0.0150
7900	0.080	39,500	0.0400
8000 (maximum load)	0.120	40,000	0.0600
7950	0.160	39,700	0.0800
7600 (fracture)	0.205	38,000	0.1025

Engineering Stress and Strain The results of a single test apply to all sizes and cross-sections of specimens for a given material if we convert the force to stress and the distance between gage marks to strain. **Engineering stress** and **engineering strain** are defined by the following equations,

$$\text{Engineering stress} = \sigma = \frac{F}{A_0} \quad (6-4)$$

$$\text{Engineering strain} = \epsilon = \frac{\Delta l}{l_0}, \quad (6-5)$$

where A_0 is the *original* cross-sectional area of the specimen before the test begins, l_0 is the *original* distance between the gage marks, and Δl is the change in length after

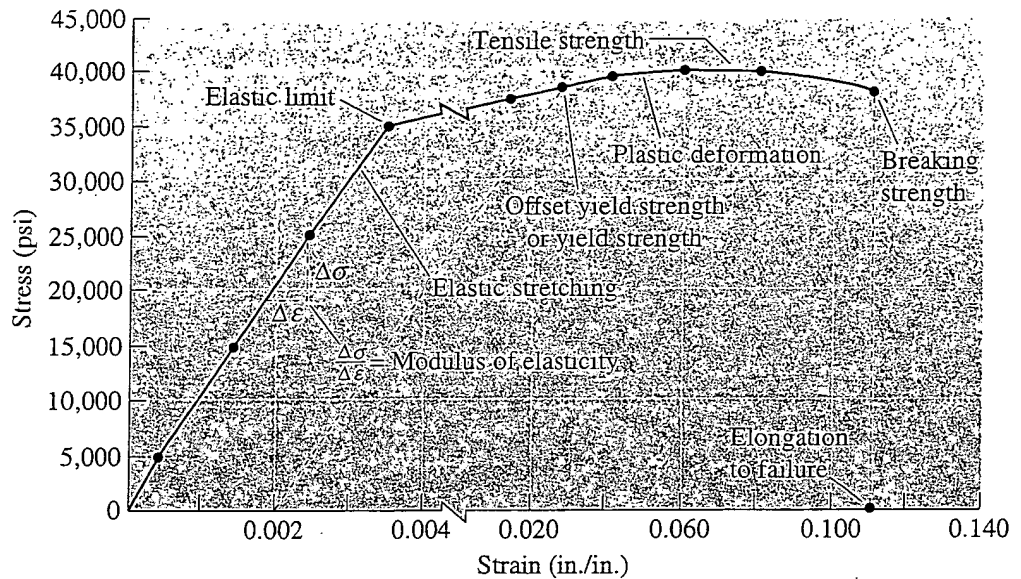


Figure 6-10 The stress-strain curve for an aluminum alloy from Table 6-1.

force F is applied. The conversions from load and sample length to stress and strain are included in Table 6-1. The stress-strain curve (Figure 6-10) is used to record the results of a tensile test.

EXAMPLE 6-1 Tensile Testing of Aluminum Alloy

Convert the change in length data in Table 6-1 to engineering stress and strain and plot a stress-strain curve.

SOLUTION

For the 1000-lb load:

$$\sigma = \frac{F}{A_0} = \frac{1000 \text{ lb}}{(\pi/4)(0.505 \text{ in})^2} = \frac{1000 \text{ lb}}{0.2 \text{ in}^2} = 5000 \text{ psi}$$

$$\epsilon = \frac{\Delta L}{L_0} = \frac{0.001 \text{ in}}{2.000 \text{ in}} = 0.0005 \text{ in/in}$$

The results of similar calculations for each of the remaining loads are given in Table 6-1 and are plotted in Figure 6-10.

Units Many different units are used to report the results of the tensile test. The most common units for stress are pounds per square inch (psi) and MegaPascals (MPa). The units for strain include inch/inch, centimeter/centimeter, and meter/meter. The conversion factors for stress are summarized in Table 6-2. Because strain is dimensionless, no conversion factors are required to change the system of units.

TABLE 6-2 Units and conversion factors

1 pound (lb) = 4.448 Newtons (N)
1 psi = pounds per square inch
1 MPa = MegaPascal = MegaNewtons per square meter (MN/m ²) = Newtons per square millimeter (N/mm ²) = 1,000,000 Pa
1 GPa = 1000 MPa = GigaPascal
1 ksi = 1000 psi = 6.895 MPa
1 psi = 0.006895 MPa
1 MPa = 0.145 ksi = 145 psi

EXAMPLE 6-2 *Design of a Suspension Rod*

An aluminum rod is to withstand an applied force of 45,000 pounds. To assure a sufficient safety, the maximum allowable stress on the rod is limited to 25,000 psi. The rod must be at least 150 in. long but must deform elastically no more than 0.25 in. when the force is applied. Design an appropriate rod.

SOLUTION

We can use the definition of engineering stress to calculate the required cross-sectional area of the rod:

$$A_0 = \frac{F}{\sigma} = \frac{45,000}{25,000} = 1.8 \text{ in.}^2$$

The rod could be produced in various shapes, provided that the cross-sectional area is 1.8 in.². For a round cross-section, the minimum diameter to assure that the stress is not too high is:

$$A_0 = \frac{\pi d^2}{4} = 1.8 \text{ in.}^2 \quad \text{or} \quad d = 1.51 \text{ in.}$$

The maximum allowable elastic deformation is 0.25 in. From the definition of engineering strain:

$$\frac{\Delta l}{l_0} = \frac{0.25 \text{ in.}}{l_0}$$

From Figure 6-10, the strain expected for a stress of 25,000 psi is 0.0025 in./in. If we use the cross-sectional area determined previously, the maximum length of the rod is:

$$0.0025 = \frac{\Delta l}{l_0} = \frac{0.25 \text{ in.}}{l_0} \quad \text{or} \quad l_0 = 100 \text{ in.}$$

However, the minimum length of the rod is specified as 150 in. To produce a longer rod, we might make the cross-sectional area of the rod larger. The minimum strain allowed for the 150-in. rod is:

$$\epsilon = \frac{\Delta l}{l_0} = \frac{0.25 \text{ in.}}{150 \text{ in.}} = 0.001667 \text{ in./in.}$$

The stress, from Figure 6-10, is about 16,670 psi, which is less than the maximum of 25,000 psi. The minimum cross-sectional area then is:

$$A_0 = \frac{F}{\sigma} = \frac{45,000 \text{ psi}}{16,670 \text{ lb}} = 2.70 \text{ in.}^2$$

In order to satisfy both the maximum stress and the minimum elongation requirements, cross-sectional area of the rod must be at least 2.7 in.², or a minimum diameter of 1.85 in.

Yield Strength As we apply stress to a material, the material initially exhibits elastic deformation. The strain that develops is completely recovered when the applied stress is removed. However, as we continue to increase the applied stress the material begins to exhibit both elastic and plastic deformation. The material eventually "yields" to the applied stress. The critical stress value needed to initiate plastic deformation is defined as the **elastic limit** of the material. In metallic materials, this is usually the stress required for dislocation motion, or slip to be initiated. In polymeric materials, this stress will correspond to disentanglement of polymer molecule chains or sliding of chains past each other. The **proportional limit** is defined as the level of stress above which the relationship between stress and strain is not linear.

In most materials the elastic limit and proportional limit are quite close. However, neither the elastic limit nor the proportional limit values can be determined precisely. Measured values depend on the sensitivity of the equipment used. We, therefore, define them at an **offset strain value** (typically, but not always, 0.002 or 0.2%). We then draw a line starting with this offset value of strain and draw a line parallel to the linear portion of the engineering stress-strain curve. The stress value corresponding to the intersection of this line and the engineering stress-strain curve is defined as the **offset yield strength**, also often stated as the **yield strength**. The 0.2% offset yield strength for gray cast iron is 40,000 psi as shown in Figure 6-11(a). Engineers normally prefer to use the offset yield strength for design purposes.

For some materials the transition from elastic deformation to plastic flow is rather abrupt. This transition is known as the **yield point phenomenon**. In these materials, as the plastic deformation begins the stress value drops first from the *upper yield point* (σ_2) [Figure 6-11(b)]. The stress value then decreases and oscillates around an average value defined as the *lower yield point* (σ_1). For these materials, the yield strength is usually defined from the 0.2% strain offset as shown in Figure 6-11(a).

The stress-strain curve for certain low-carbon steels displays a double yield point [Figure 6-11(b)]. The material is expected to plastically deform at stress σ_1 . However, small interstitial atoms clustered around the dislocations interfere with slip and raise the yield point to σ_2 . Only after we apply the higher stress σ_2 do the dislocations slip. After slip begins at σ_2 , the dislocations move away from the clusters of small atoms and continue to move very rapidly at the lower stress σ_1 .

When we design parts for load-bearing applications we prefer little or no plastic deformation. As a result we must select a material such that the design stress is considerably lower than the yield strength at the temperature at which the material will be used. We can also make the component cross-section larger so that the applied force produces a stress that is well below the yield strength. On the other hand, when we want

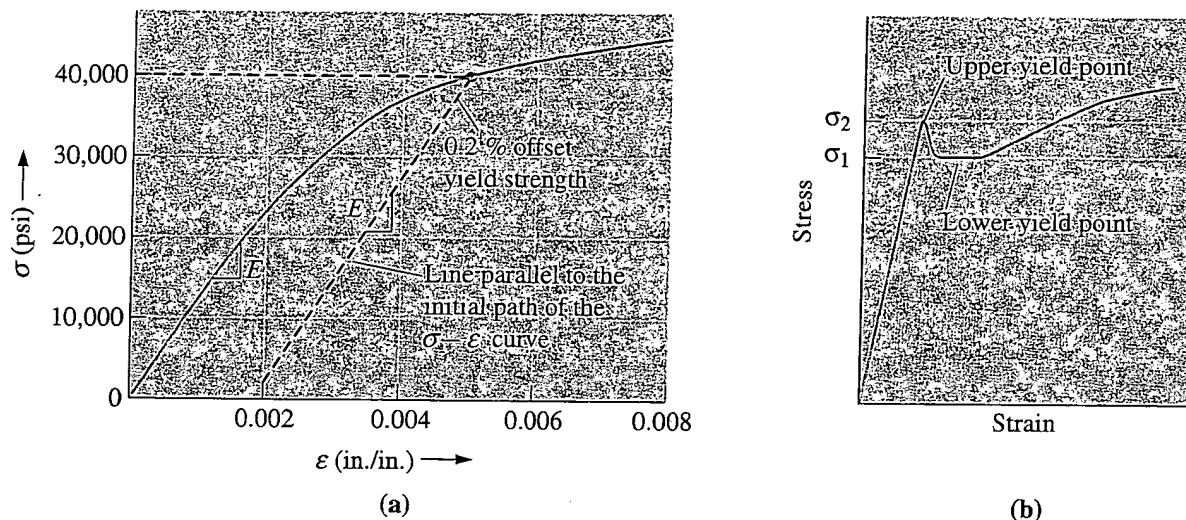


Figure 6-11 (a) Determining the 0.2% offset yield strength in gray cast iron, and (b) upper and lower yield point behavior in a low-carbon steel.

to shape materials into components (e.g., take a sheet of steel and form a car chassis), we need to apply stresses that are well above the yield strength.

Tensile Strength The stress obtained at the highest applied force is the **tensile strength** (σ_{TS}), which is the maximum stress on the engineering stress-strain curve. In many ductile materials, deformation does not remain uniform. At some point, one region deforms more than others and a large local decrease in the cross-sectional area occurs (Figure 6-12). This locally deformed region is called a “neck.” This phenomenon is known as **necking**. Because the cross-sectional area becomes smaller at this point, a lower force is required to continue its deformation, and the engineering stress, calculated from the *original* area A_0 , decreases. The tensile strength is the stress at which necking begins in ductile materials. Many ductile metals and polymers show the phe-

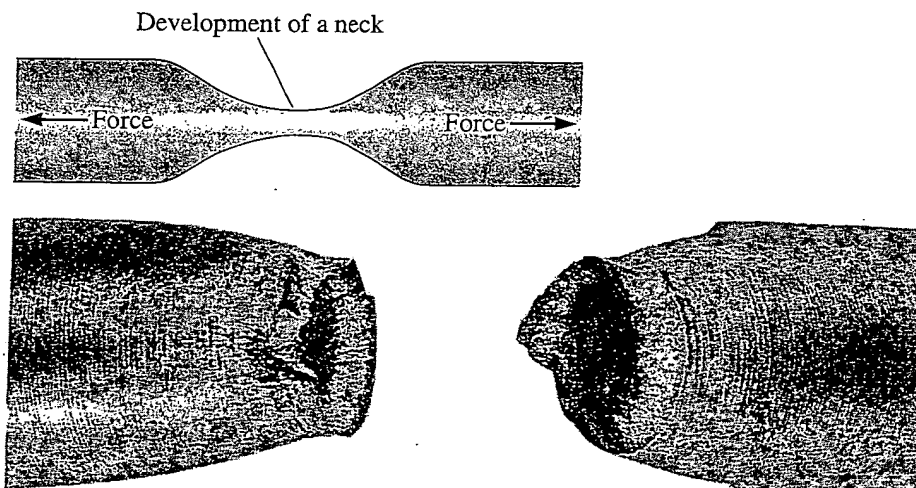


Figure 6-12 Localized deformation of a ductile material during a tensile test produces a necked region. The micrograph at the bottom shows necked region in a fractured sample.

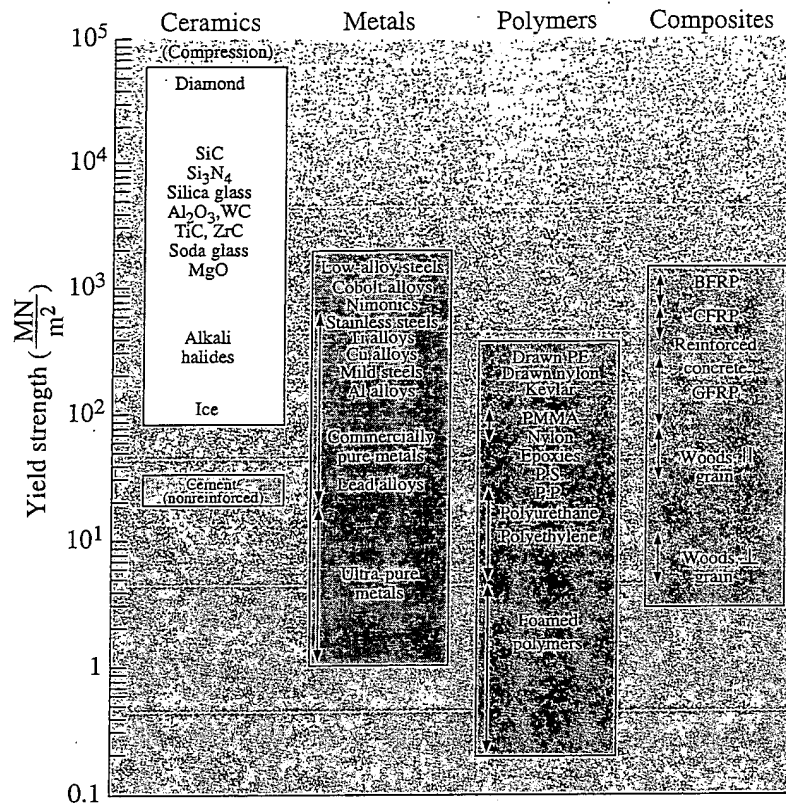


Figure 6-13 Typical yield strength values for different engineered materials. (Source: Reprinted from *Engineering Materials I, Second Edition*, M.F. Ashby and D.R.H. Jones, 1996, Fig. 8-12, p. 85. Copyright © Butterworth-Heinemann. Reprinted with permission from Elsevier Science.)

nomenon of necking. In compression testing, the materials will bulge, thus necking is seen only in a tensile test.

Figure 6-13 shows typical yield strength values for different engineered materials. The yield strength of pure metals is smaller. For example, ultra-pure metals have a yield strength of $\sim (1 - 10 \frac{\text{MN}}{\text{m}^2})$. On the other hand, the yield strength of alloys is higher. Strengthening in alloys is achieved using different mechanisms described before (e.g., grain size, solid solution formation, strain hardening, etc.). The yield strength of plastics and elastomers is generally lower than metals and alloys, ranging up to about $(10 - 100 \frac{\text{MN}}{\text{m}^2})$. The values for ceramics are for compressive strength (obtained using a hardness test). Tensile strength of most ceramics is much lower ($\sim 100 - 200 \text{ MPa}$). The tensile strength of glasses is about $\sim 70 \text{ MPa}$ and depends on surface flaws.

Elastic Properties The modulus of elasticity, or *Young's modulus* (E), is the slope of the stress-strain curve in the elastic region. This relationship is **Hooke's Law**: [6]

$$E = \frac{\sigma}{\epsilon} \quad (6-6)$$

The modulus is closely related to the binding energies (Figure 2-26). A steep slope in the force-distance graph at the equilibrium spacing indicates that high forces are required to separate the atoms and cause the material to stretch elastically. Thus, the material has a

TABLE 6-3 Elastic properties and melting temperature (T_m) of selected materials

Material	T_m ($^{\circ}\text{C}$)	E (psi)	Poisson's ratio (μ)
Pb	327	2.0×10^6	0.45
Mg	650	6.5×10^6	0.29
Al	660	10.0×10^6	0.33
Cu	1085	18.1×10^6	0.36
Fe	1538	30.0×10^6	0.27
W	3410	59.2×10^6	0.28
Al_2O_3	2020	55.0×10^6	0.26
Si_3N_4		44.0×10^6	0.24

high modulus of elasticity. Binding forces, and thus the modulus of elasticity, are typically higher for high melting point materials (Table 6-3). In metallic materials, modulus of elasticity is considered microstructure *insensitive* property since the value is dominated strongly by the strength of atomic bonds. Grain size or other microstructural features do not have a very large effect on the Young's modulus. Note that Young's modulus does depend on such factors as orientation of a single crystal material (i.e., it depends upon crystallographic direction). For ceramics, the Young's modulus depends on the level of porosity. Young's modulus of a composite depends upon the stiffness of the individual components.

Young's modulus is a measure of the stiffness of a component. A stiff component, with a high modulus of elasticity, will show much smaller changes in dimensions if the applied stress is relatively small and, therefore, causes only elastic deformation. Figure 6-14 compares the elastic behavior of steel and aluminum. If a stress of 30,000 psi is applied to each material, the steel deforms elastically 0.001 in./in.; at the same stress, aluminum deforms 0.003 in./in. In general, most engineers view stiffness as a function of both the Young's modulus and the geometry of a component.

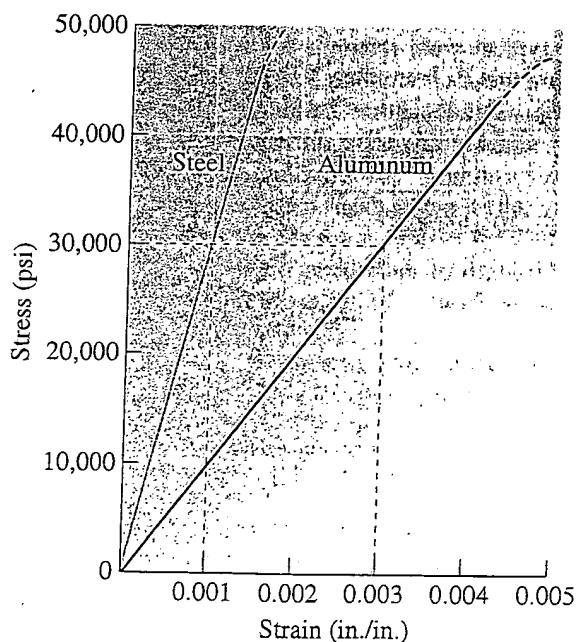


Figure 6-14 Comparison of the elastic behavior of steel and aluminum. For a given stress, aluminum deforms elastically three times as much as does steel.

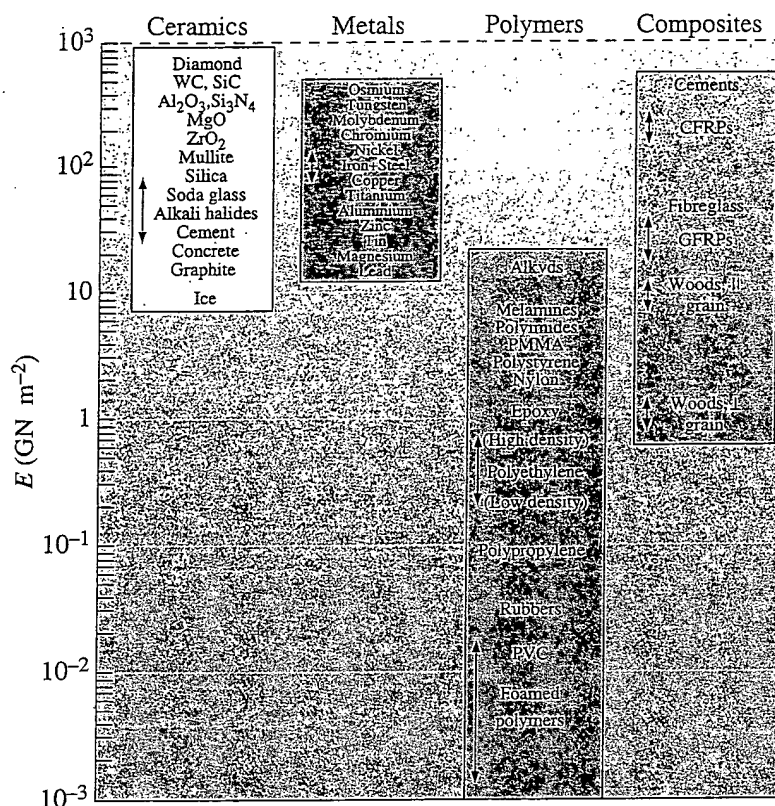


Figure 6-15 Range of elastic moduli for different engineered materials. (Source: Reprinted from Engineering Materials I, Second Edition, M.F. Ashby and D.R.H. Jones, 1996, Fig. 3-5, p. 35, Copyright © 1996 Butterworth-Heinemann. Reprinted with permission from Elsevier Science.)

Figure 6-15 shows the ranges of elastic moduli for different engineered materials. The modulus of elasticity of plastics is much smaller than that for metals or ceramics and glasses. For example, the modulus of elasticity of nylon is 2.7 GPa ($\sim 0.4 \times 10^6$ psi); the modulus of glass fibers is 72.4 GPa ($\sim 10.5 \times 10^6$ psi). The Young's modulus of composites such as glass fiber-reinforced composites (GFRP) or carbon fiber-reinforced composites (CFRP) lies between the values for the matrix polymer and the fiber phase (carbon or glass fibers) and depends upon their relative volume fractions. The Young's modulus of many alloys and ceramics is higher, generally ranging up to 413.7 GPa ($\sim 60 \times 10^6$ psi). Ceramics, because of the strength of ionic and covalent bonds, have the highest elastic moduli.

Poisson's ratio, μ , relates the longitudinal elastic deformation produced by a simple tensile or compressive stress to the lateral deformation that occurs simultaneously:

$$\mu = \frac{-\epsilon_{\text{lateral}}}{\epsilon_{\text{longitudinal}}} \quad (6-7)$$

For many metals in the elastic region the Poisson's ratio is typically about 0.3 (Table 6-3). During a tensile test the ratio increases beyond yielding to about 0.5 since during the plastic deformation volume remains constant. Some interesting structures exhibit negative Poisson's ratio.[7]

The **modulus of resilience** (E_r), the area contained under the elastic portion of a stress-strain curve, is the elastic energy that a material absorbs during loading and subsequently releases when the load is removed. For linear elastic behavior:

$$E_r = \left(\frac{1}{2}\right)(\text{yield strength})(\text{strain at yielding}) \quad (6-8)$$

The ability of a spring or a golf ball to perform satisfactorily depends on a high modulus of resilience.

Tensile Toughness The energy absorbed by a material prior to fracturing is known as **tensile toughness** and is sometimes measured as the area under the true stress-strain curve (also known as **work of fracture**). We will define true stress and true strain in Section 6-5. Since it is easier to measure engineering stress-strain, engineers often equate tensile toughness to the area under the engineering stress-strain curve.

EXAMPLE 6-3 Young's Modulus of Aluminum Alloy

From the data in Example 6-1, calculate the modulus of elasticity of the aluminum alloy. Use the modulus to determine the length after deformation of a bar of initial length of 50 in. Assume that a level of stress of 30,000 psi is applied.

SOLUTION

When a stress of 35,000 psi is applied, a strain of 0.0035 in./in. is produced. Thus:

$$\text{Modulus of elasticity} = E = \frac{\sigma}{\epsilon} = \frac{35,000 \text{ psi}}{0.0035} = 10 \times 10^6 \text{ psi}$$

From Hooke's law

$$\epsilon = \frac{\sigma}{E} = \frac{30,000 \text{ psi}}{10 \times 10^6} = 0.0003 = \text{in./in.} = \frac{l - l_0}{l_0}$$

$$l = l_0 + \epsilon l_0 = 50 + (0.003)(50) = 50.15 \text{ in.}$$

Ductility Ductility measures the amount of deformation that a material can withstand without breaking. We can measure the distance between the gage marks on our specimen before and after the test. The **percent elongation** describes the permanent plastic deformation before failure (i.e., the elastic deformation recovered after fracture is not included). Note that the strain to failure is smaller than strain at the breaking point.

$$\% \text{ Elongation} = \frac{l_f - l_0}{l_0} \times 100 \quad (6-9)$$

where l_f is the distance between gage marks after the specimen breaks.

A second approach is to measure the percent change in the cross-sectional area at the point of fracture before and after the test. The **percent reduction in area** describes the amount of thinning undergone by the specimen during the test:

$$\% \text{ Reduction in area} = \frac{A_0 - A_f}{A_0} \times 100 \quad (6-10)$$

where A_f is the final cross-sectional area at the fracture surface.

Ductility is important to both designers of load-bearing components and manufacturers of components (bars, rods, wires, plates, I-beams, fibers, etc.) utilizing materials processing. The designer of a component prefers a material that displays at least some ductility, so that, if the applied stress is too high, the component can take some of

the stress by deforming and not fail via a brittle fracture. Fabricators of engineering components (metallic and polymeric) want a ductile material in order to form complicated shapes without breaking the material in the process. Ductility of materials depends on temperature and strain rate.

EXAMPLE 6-4 Ductility of an Aluminum Alloy

The aluminum alloy in Example 6-1 has a final length after failure of 2.195 in. and a final diameter of 0.398 in. at the fractured surface. Calculate the ductility of this alloy.

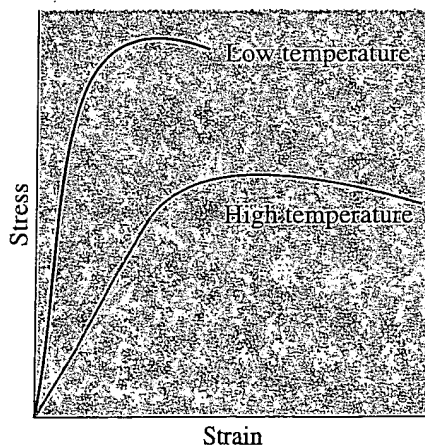
SOLUTION

$$\% \text{Elongation} = \frac{l_f - l_0}{l_0} \times 100 = \frac{2.195 - 2.000}{2.000} \times 100 = 9.75\%$$

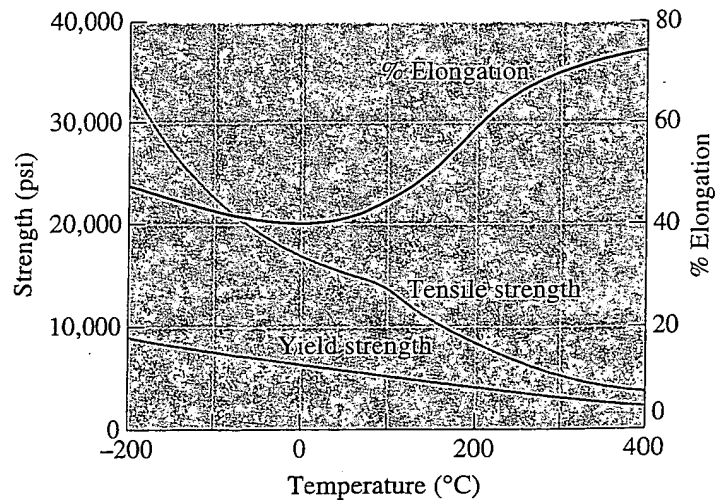
$$\begin{aligned} \% \text{Reduction in area} &= \frac{A_0 - A_f}{A_0} \times 100 \\ &= \frac{(\pi/4)(0.505)^2 - (\pi/4)(0.398)^2}{(\pi/4)(0.505)^2} \times 100 \\ &= 37.9\% \end{aligned}$$

The final length is less than 2.205 in. (see Table 6-1) because, after fracture, the elastic strain is recovered.

Effect of Temperature Mechanical properties of materials depend on temperature (Figure 6-16). Yield strength, tensile strength, and modulus of elasticity decrease at higher temperatures, whereas ductility commonly increases. A materials fabricator may wish to deform a material at a high temperature (known as *hot working*) to take



(a)



(b)

Figure 6-16 The effect of temperature (a) on the stress-strain curve and (b) on the tensile properties of an aluminum alloy.

advantage of the higher ductility and lower required stress. Some of you may have heard the sayings “heat and beat” or “strike while the iron is hot.” The origin of these phrases is related to the ductility many metallic materials develop when heated to higher temperatures. We use the term “high temperature” here with a note of caution. Essentially, a high temperature is something that is approaching the melting temperature. Thus, 500°C is a high temperature for aluminum alloys; however, it is a relatively low temperature for the processing of steels. In metals, the yield strength decreases rapidly at higher temperatures since metallic materials can show a decreased dislocation density and an increase in grain size via grain growth (Chapter 5), or “recrystallize” into new grains that are essentially dislocation free (as described later in Chapter 7). Similarly, any strengthening that may have occurred because of formation of ultrafine precipitates (Chapter 4) may also decrease as the precipitates begin to either grow in size or dissolve into the matrix. We will discuss these effects in greater detail in later chapters. When temperatures are reduced, many, but not all, metals and alloys become brittle.

Increased temperatures also play an important role in forming polymeric materials as well as inorganic glasses. In many polymer-processing operations, such as extrusion or the stretch-blow process (Chapter 4), the increased ductility of polymers at higher temperature is advantageous. Again, a word of caution concerning the use of the term “high temperature”: For polymers, the term “higher temperature” would generally mean a temperature higher than the glass temperature (T_g). In some sources, you will see T_g described as the glass transition temperature. There is no “transition” at this temperature. For our purpose, glass temperature is a temperature below which materials behave as brittle materials. Above the glass temperature plastics become ductile. Glass temperature is not a fixed temperature, but depends upon rate of cooling as well as the polymer molecular weight distribution. Many plastics are ductile at room temperature because their glass temperatures are *below* room temperature. To summarize, many polymeric materials will become harder and more brittle as they are exposed to temperatures that are below their glass temperatures. The reasons for loss of ductility at lower temperatures in polymers and metallic materials are different. However, this is a factor that played a role in failures of the *Titanic* in 1912 and the *Challenger* in 1986.

Ceramic and glassy materials are generally considered brittle at room temperatures. As the temperature increases, glasses can flow better and become more ductile. As a result, glass processing (e.g., fiber drawing or bottle manufacturing) is performed at high temperatures. Polycrystalline ceramics also can gain increased ductility at higher temperatures via mechanisms that involve grain boundary sliding and other phenomena. This is discussed in Section 6-21.

6-5

True Stress and True Strain

The decrease in engineering stress beyond the tensile strength point on an engineering stress-strain curve is related to the definition of engineering stress. We used the original area A_0 in our calculations, but this is not precise because the area continually changes. We define **true stress** and **true strain** by the following equations:

$$\text{True stress} = \sigma_t = \frac{F}{A} \quad (6-11)$$

$$\text{True strain} = \int \frac{dl}{l} = \ln \left(\frac{l}{l_0} \right) = \ln \left(\frac{A_0}{A} \right), \quad (6-12)$$

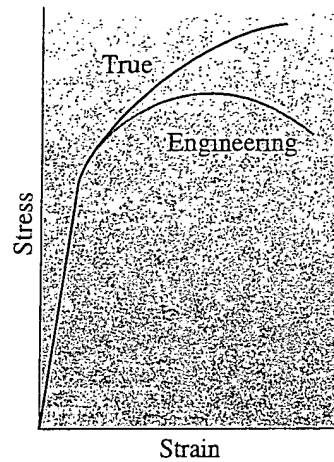


Figure 6-17

The relation between the true stress-true strain diagram and engineering stress-engineering strain diagram. The curves are identical to the yield point.

where A is the actual area at which the force F is applied. The expression $\ln(A_0/A)$ can only be used after necking begins, after which volume remains constant and $\frac{A_0}{l_0} = \frac{A}{l}$.

The true stress-strain curve is compared with the engineering stress-strain curve in Figure 6-17. True stress continues to increase after necking because, although the load required decreases, the area decreases even more.

For structural applications we often do not require true stress and true strain. When we exceed the yield strength, the material deforms. The component has failed because it no longer has the original intended shape. Furthermore, a significant difference develops between the two curves only when necking begins. But when necking begins, our component is grossly deformed and no longer satisfies its intended use. Engineers dealing with materials processing require data related to true stress and strain.

EXAMPLE 6-5 True Stress and True Strain Calculation

Compare engineering stress and strain with true stress and strain for the aluminum alloy in Example 6-1 at (a) the maximum load and (b) fracture. The diameter at maximum load is 0.497 in. and at fracture is 0.398 in.

SOLUTION

(a) At the tensile or maximum load:

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{8000 \text{ lb}}{(\pi/4)(0.505 \text{ in.})^2} = 40,000 \text{ psi}$$

$$\text{True stress} = \frac{F}{A} = \frac{8000 \text{ lb}}{(\pi/4)(0.497 \text{ in.})^2} = 41,237 \text{ psi}$$

$$\text{Engineering strain} = \frac{l - l_0}{l_0} = \frac{2.120 - 2.000}{2.000} = 0.060 \text{ in./in.}$$

$$\text{True strain} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{2.120}{2.000}\right) = 0.058 \text{ in./in.}$$

(b) At fracture

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{7600 \text{ lb}}{(\pi/4)(0.505 \text{ in.})^2} = 38,000 \text{ psi}$$

$$\text{True stress} = \frac{F}{A} = \frac{7600}{(\pi/4)(0.398 \text{ in.})^2} = 61,090 \text{ psi}$$

$$\text{Engineering strain} = \frac{\Delta l}{l_0} = \frac{0.205}{2.000} = 0.1025 \text{ in./in.}$$

$$\text{True strain} = \ln\left(\frac{A_0}{A_f}\right) = \ln\left[\frac{(\pi/4)(0.505)^2}{(\pi/4)(0.398)^2}\right]$$

$$= \ln(1.610) = 0.476 \text{ in./in.}$$

The true stress becomes much greater than the engineering stress only after necking begins.

6-6

The Bend Test for Brittle Materials

In ductile metallic materials, the engineering stress-strain curve typically goes through a maximum; this maximum stress is the tensile strength of the material. Failure occurs at a lower stress after necking has reduced the cross-sectional area supporting the load. In more brittle materials, failure occurs at the maximum load, where the tensile strength and breaking strength are the same. In brittle materials, including many ceramics, yield strength, tensile strength, and breaking strength are all the same (Figure 6-18).

In many brittle materials, the normal tensile test cannot easily be performed because of the presence of flaws at the surface. Often, just placing a brittle material in the grips of the tensile testing machine causes cracking. These materials may be tested using the bend test [Figure 6-19(a)]. By applying the load at three points and causing bending, a tensile force acts on the material opposite the midpoint. Fracture begins

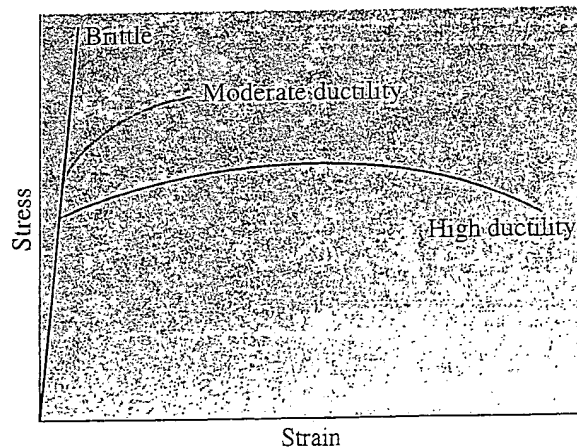


Figure 6-18

The stress-strain behavior of brittle materials compared with that of more ductile materials.

Newtonian Materials in which the shear stress and shear strain rate are linearly related (e.g., light oil or water).

Non-Newtonian Materials in which shear stress and shear strain rate are not linearly related, these materials are shear thinning or shear thickening (e.g., polymer melts, slurries, paints, etc.).

Notch sensitivity Measures the effect of a notch, scratch, or other imperfection on a material's properties, such as toughness or fatigue life.

Offset strain value A value of strain (e.g., 0.002) used to obtain the offset yield stress value.

Offset yield strength A stress value obtained graphically that describes the stress that gives no more than a specified amount of plastic deformation. Most useful for designing components. Also, simply stated as the yield strength.

Percent elongation The total percentage increase in the length of a specimen during a tensile test.

Percent reduction in area The total percentage decrease in the cross-sectional area of a specimen during the tensile test.

Plastic deformation or strain Permanent deformation of a material when a load is applied, then removed.

Poisson's ratio The ratio between the lateral and longitudinal strains in the elastic region.

Proportional limit A level of stress above which the relationship between stress and strain is not linear.

Pseudoplastics (shear thinning) Materials in which the apparent viscosity decreases with increasing rate of shear.

Rheometer An instrument used to measure rheological properties such as viscosity, yield stress, shear thinning behavior, etc. of a material.

Rheoplectic behavior Materials that show shear thickening and also an apparent viscosity that at a constant rate of shear increases with time.

Rotating cantilever beam test An older test for fatigue testing.

Rupture time The time required for a specimen to fail by creep at a particular temperature and stress.

S-N curve (also known as the Wöhler curve) A graph showing stress as a function of number of cycles in fatigue.

Shear modulus (G) The slope of the linear part of the shear stress-shear strain curve.

Shear-strain rate Time derivative of shear strain. See "Strain rate."

Shear thickening (dilatant) Materials in which the apparent viscosity increases with increasing rate of shear.

Shear thinning (pseudoplastics) Materials in which the apparent viscosity decreases with increasing rate of shear.

Shot peening A process in which metal spheres are shot at a component. This leads to a residual compressive stress at the surface of a component and this enhances fatigue life.

Stiffness A qualitative measure of the elastic deformation produced in a material. A stiff material has a high modulus of elasticity. Stiffness also depends upon geometry.

Weibull distribution A mathematical distribution showing the probability of failure or survival of a material as a function of the stress.

Weibull modulus (m) A parameter related to the Weibull distribution. It is an indicator of the variability of the strength of materials resulting from a distribution of flaw sizes.

Wöhler curve Graph showing fatigue stress as a function of number of cycles (also known as the S-N curve).

Yield point phenomenon An abrupt transition, seen in some materials, from elastic deformation to plastic flow.

Yield strength A stress value obtained graphically that describes no more than a specified amount of deformation (usually 0.002). Also known as offset yield strength.

Young's modulus The slope of the linear part of the stress-strain curve in the elastic region, same as modulus of elasticity.

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PROBLEMS

Section 6-1 Technological Significance

6-1 Explain the role of mechanical properties in load-bearing applications using real-world examples.

6-2 Explain the importance of mechanical properties in functional applications (e.g., optical, magnetic, electronic, etc.) using real-world examples.